

DIELECTRIC SPECTROSCOPY IN TIME AND FREQUENCY DOMAIN FOR HV POWER EQUIPMENT (TRANSFORMERS, CABLES ETC.)

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Abstract: The main aim of this lecture is to present and to recall the fundamentals of dielectric response in time- and frequency- domain by introducing into the basic equations. From these fundamentals, measuring and diagnostic methods can be derived which become more and more attractive for a condition based maintenance of electric power equipment which has to be applied in future. Hints to available instruments are provided and, in a final chapter, an example for the application of a time domain method based on investigations concerned with HV power transformer insulation systems is provided.

1 Introduction

Today, the catchword in utility companies is condition-based or predictive testing and maintenance, or even life management, as opposed to time-based or preventive maintenance only. The reasons for this evolution are well known. In North America, for instance, their roots can be found in restructuring and re-regulation of the Electric Utility Industry, and here in Europe, it was the adoption of the "Single Market Directive" which became the norm in Febr. 1999, whereas it was still the exception many years before [1]. The main issue of this de-regulation of the electricity market, which becomes now subdivided into independent power producers, transmission companies, system operators and distribution companies, is to encourage competition whilst still maintaining basic public policy and service objectives.

All partners within this new scheme are thus forced to cut costs in maintenance and operation without endangering steady supply of electricity to demanding customers. Costs can be reduced first of all by a transition from time-based maintenance (TBM) to condition based maintenance (CBM), if the actual conditions of the expensive high voltage (HV) components within the electric power transmission systems are reliably known. The application of "unscheduled maintenance", the philosophy of which is based on a reactive mode of operation, will not at all reduce costs. Unscheduled maintenance means that only then repairs and maintenance will be made if the equipment, as e.g. a transformer or cable, breaks down. But this causes in general a downtime of the electricity supply so that breakdowns become much more costly than planned maintenance. A **CBM** based on diverse, reliable diagnostic tools should be applied today.

Driving forces for the development and application of improved diagnostic methods are the steadily

increasing age of expensive HV components. In many parts of the world, the majority of e.g. large power transformers has been installed in the 60's of the last century. Also, cable technology did change at this time and the first generations of PE or XLPE cables are still prone to breakdowns. All these facts are very well known.

It is not the aim of this contribution to discuss the full complexity of all the different diagnostic techniques as already successfully applied to different HV components. Most of the dangerous break-downs, however, are caused by **ageing effects of the HV insulation systems** as used within these components, and there is still some lack of appropriate tools to diagnose insulation materials non-destructively and reliably in the field of application. New methods have been published in the last decade and even before, for which reliable diagnostics are claimed. Many of these methods are based on **changes of dielectric properties** of the insulation, whose basics are often not very well known. Therefore, this contribution will predominantly introduce into such basics but will also provide some hints to more recent instruments, which are able to quantify dielectric properties in the field.

2 Background of Dielectric Response

Experience shows that most of electric power engineers are not too familiar with the fundamentals of "dielectric response functions" and their background. The following short introduction may contribute to close this gap.

Every kind of insulation material consists at an atomic level of negative and positive charges balancing each other in microscopic as well as in more macroscopic scales (if no uni-polar charge was deposited within the material before by well known charging effects). Macroscopically, some localised space charge may be present, but even then an overall charge neutrality exists.

As soon as the material is exposed to an electric field (as generated by a voltage across electrodes between which the dielectric is embedded), very different kinds of **dipoles** become excited even within atomic scales. A local charge imbalance is thus "induced" within the neutral species (atoms or molecules) as the "centres of gravity" for the equal amount of positive and negative charges, $\pm q$, become separated by a small distance d , thus creating a dipole with a **dipole moment**, $p = qd$, which is related to the "local" or "microscopic"

electric field E acting in close vicinity of the species. Thus, the dipole moment can also be written as $p = \alpha E$, where α is the "*polarisability*" of the species or material under consideration. Note that p , d and E are vectors not marked here. As the distance d will be different for different species as well as the number of dipoles per unit volume, also their polarisability is different. Due to chemical interactions between dissimilar atoms forming molecules, many molecules will have a constant and stable distance d between the charge centers thus forming "permanent dipole moments", which are in general not uniformly distributed within the matter as long as no external field is applied. (Note, that any kind of "permanent polarisation", as effective in *electrets* or *ferroelectrics*, is not considered here). The macroscopic effect of the polarisability of individual species is finally manifested in a general relation between the **macroscopic polarisation P** and the number of polarised species N per unit volume of the matter. These relationships are known, but not treated here.

But let us recall now the *main mechanisms producing polarisation P* : "**Electronic Polarisation**" is effective in every atom or molecule as the centre of gravity of the electrons surrounding the positive atomic cores will be displaced by the electric field E . This effect is extremely fast and thus effective up to optical frequencies. - "**Ionic (or molecular) Polarisation**" refers to matter containing molecules forming ions, which do not separate by low electric fields or working temperatures. - "**Dipolar (or orientation) Polarisation**" belongs to matter containing molecules with *permanent* dipole moments with orientations statistically distributed due to the action of thermal energy. Under the influence of E , the dipoles will be oriented only partially, so again, a linear dependency of P and E exists. Ionic and dipolar polarisation are still quite fast effects and may follow AC frequencies up to MHz or GHz. - "**Interfacial Polarisation**" is predominantly effective in insulating materials composed of different dielectric materials *as e.g. oil impregnated paper/cellulose*. The mismatch of the products permittivity by electric conductivity for the different dielectrics forces movable positive and negative charges to become deposited on the interfaces of different insulating materials, thus forming dipoles. This phenomena is often *very slow* and in general active in a very low frequency range up to power frequencies. - Finally, **hopping of charge carriers** between localised sites of charges may occur creating also polarisation. This is in general also a slow process as e.g. active in cable materials (PE etc.). For more detail see e.g. [2, 3].

In summary, the dielectric polarisation is the result of a relative shift of positive and negative charges in the matter. During all of these processes, the electric field is therefore *not able to force the charges to escape from the matter*, which would cause inherent **electric conduction!**

Dielectric Response Methods are based on fundamental interactions between well known electric quantities: Usually, HV insulation materials (also called dielectrics) are isotropic and in general homogeneous, at least at macroscopic scales. Then, the vectors of (macroscopic) polarisation P and the electric field E are of equal direction and interrelated by

$$P = \chi \epsilon_0 E. \quad (1)$$

Here, χ is the (dielectric) **susceptibility** of the matter, a dimensionless number which is **zero** for ideal vacuum. Thus, the susceptibility χ accounts for all kinds of polarisation processes as effective within a dielectric. ϵ_0 is the **permittivity of vacuum** ($= 8.85419 \times 10^{-12}$ [As/Vm]), a number with units relating the unit for electric field (V/m) to that of electric displacement (As/m²). This provides already a hint that all polarisation processes induce also electric charges at the electrodes, between which the dielectric is sandwiched.

From equn. (1) it can well be deduced that the polarisation P will change or vanish if the field E is changed or set to zero. A reduction of E will thus lead to a *depolarisation* process, which will follow with some *delay or retardation* to the reduction of E . Dielectric properties become thus *dynamic* events which can be detected in **time-** as well as in **frequency domain**.

3 Dielectric response in time domain

In a *vacuum-insulated* electrode arrangement, the vector of **electric displacement** (or "*dielectric flux density*" or "*electrical induction*") D is exactly proportional to the electric field E ,

$$D = \epsilon_0 E \quad (2)$$

or, if the electric field is generated by a time-varying voltage,

$$D(t) = \epsilon_0 E(t). \quad (2a)$$

Here, ϵ_0 is again the permittivity of vacuum. The origin of D and E is in general provided by a voltage source connected to the electrodes of any electrode arrangement under consideration. No time delay at all will exist between both magnitudes, if the time scales considered produce still "electrostatic field conditions". Note, however, that D represents the (positive and negative) electric charges per unit area as induced at the electrode surface, these charges are the origin - sources and sinks - of all electric field lines. For time-varying fields, $E(t)$, the so called "displacement current" must be supplied by the voltage source to maintain the area charge density at the electrodes. This current is governed by dQ/dt , where Q is the total electric charge deposited on each of the electrodes.

If now the vacuum is replaced by any kind of isotropic dielectric material, the electric displace-

ment D of equ. (2) increases by its inherent (macroscopic) polarisation P as defined in equ. (1):

$$\begin{aligned} D(t) &= \varepsilon_0 E(t) + P(t) \\ &= \varepsilon_0(1 + \chi)E(t). \end{aligned} \quad (3)$$

This equation is quite essential as it separates the two kinds of charge induction! As for *isotropic* materials both vectors, P and D , are still in parallel to E , we can further on avoid bold letters to mark vectors. However, the time dependency of $P(t)$ will not any more be the same as that of $E(t)$, as the different polarisation processes have different time delays with respect to the appearance of E . This delay is obviously caused by the time-dependent behaviour of the susceptibility $\chi = \chi(t)$!

This time delay may be understood best with the following reflections: Let us assume, that a step-like constant electric field of magnitude E_0 is applied within the dielectric at any time t_0 and that this field remains constant for $t \geq t_0$. The dielectric can then be completely characterised by its time dependent susceptibility $\chi(t)$ or its specific polarisation $P(t)$ as a **response in time domain**, i.e. the formation and evolution of the different kinds of polarisation processes, which develop as well within extremely short times (as e.g. electronic polarisation) or are much slower or even very slow (as e.g. interfacial polarisation). For $t \leq t_0$, the magnitude of the susceptibility or polarisation is still zero.

Figure 1 displays this special situation, which, according to equ. (1), can be expressed as

$$P(t)/E_0 = \varepsilon_0 \chi(t) 1(t). \quad (4)$$

Here $\chi(t)$ as well as $P(t)$ represent "step response functions". The factor $1(t)$ is used to indicate the unit step. Note, however, that in fig. 1 the first part of these functions are simplified by an ideal step to account for the very fast polarisation processes, marked by an "instantaneous polarisation", $P(t = t_0) = P_\infty$. This step can in general not be recorded neither in time- nor in an adequate frequency domain. As all kinds of polarisation become finite and will settle at longer times, the polarisation becomes finally "static", $P(t \rightarrow \infty) = P_S$, i.e. for a selected time static.

Due to fig. 1, the step response of this somewhat simplified polarisation can now be written as

$$P(t) = P_\infty + (P_S - P_\infty) g(t - t_0), \quad (5)$$

where $g(t)$ is a dimensionless, monotonically increasing function. Equ. (4) may also be written as

$$P(t) = \varepsilon_0 [\chi_\infty + (\chi_S - \chi_\infty) g(t - t_0)] E_0 \quad (5a)$$

or, if *relative* permittivities, $\varepsilon = 1 + \chi$, are introduced:

$$P(t) = \varepsilon_0 [(\varepsilon_\infty - 1) + (\varepsilon_S - \varepsilon_\infty) g(t - t_0)] E_0. \quad (5b)$$

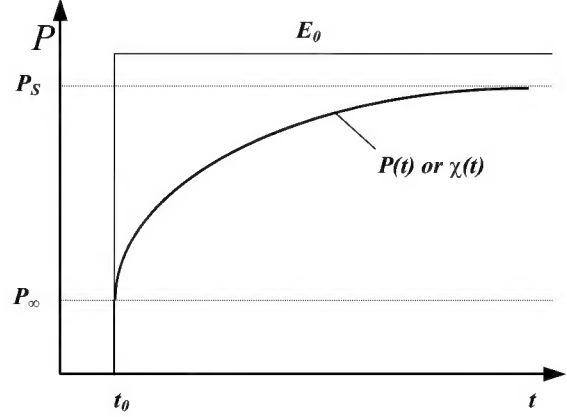


Figure 1: Polarisation of a dielectric exposed to a step field of magnitude E_0 .

As known from general circuit theory, it is now possible to compute any other time dependent polarisation $P(t)$ for *any other* time dependent excitation $E(t)$ of a test object, as the special solutions for the step excitation are already known. This can be done by means of "Duhamel's Integral" or convolution in the time domain. For the quantities as used in equ. (5a), the result is:

$$P(t) = \varepsilon_0 \chi_\infty E(t) + \varepsilon_0 \int_{-\infty}^t f(t - \tau) E(\tau) d\tau, \quad (6)$$

where $f(t)$ is the so called dielectric response function

$$\begin{aligned} f(t) &= (\chi_S - \chi_\infty) \partial g(t) / \partial t \\ &= (\varepsilon_S - \varepsilon_\infty) \partial g(t) / \partial t. \end{aligned} \quad (7)$$

$f(t)$ is obviously a **monotonically decreasing** function and inherent to the dielectric investigated.

The polarisation $P(t)$ is not an observable magnitude by itself, but it produces the *main* part of the **polarisation** (or absorption, or charging) **current** in a test object if the electric field, $E(t)$, is *suddenly* applied. But up to now, we have not yet considered any inherent or "pure" dc conductivity σ_0 , which represents the movement of the free charges in the dielectric and which is **not** involved in polarisation. As already postulated by Maxwell in 1891 [4], this field $E(t)$ generates a total current density $j(t)$, which can be written as the sum of conduction, vacuum and polarisation displacement current, i.e.:

$$\begin{aligned} j(t) &= \sigma_0 E(t) + \frac{\partial D(t)}{\partial t} \\ &= \sigma_0 E(t) + \varepsilon_0 \frac{\partial E(t)}{\partial t} + \frac{\partial P(t)}{\partial t} \end{aligned} \quad (8)$$

and with equ. (6) for $E(t) = \text{const.}$

$$j(t) = \sigma_0 E(t) + \varepsilon_0 [\varepsilon_\infty \delta(t) + f(t)] E(t) \quad (8a)$$

with $\varepsilon_\infty = 1 + \chi_\infty$.

Equation (8a) is thus a first basis for the measurement of the dielectric response function

$f(t)$. For doing so, a step-like dc "charging voltage" of magnitude U_C which must be constant and free of ripple, is suddenly switched to the test object which has been totally discharged before. Then a **polarisation current** $i_{pol}(t)$ through the test object can be recorded according to the equation

$$i_{pol}(t) = C_0 U_C \left[\frac{\sigma_0}{\epsilon_0} + \epsilon_\infty \delta(t) + f(t) \right] \quad (9)$$

where

C_0 is the geometric or vacuum capacitance of the test object, and

$\delta(t)$ is the delta function originating from the applied step voltage at $t = t_0$.

The transition from equn. (8a) to (9) is easy to perform. This polarisation current contains 3 parts: The first one is related to the intrinsic conductivity of the object, the last one represents all polarisation processes as activated during the time of voltage application and the middle part with the delta function can not be recorded in practice due to the large dynamic range of the current amplitudes.

A polarisation current measurement can be stopped if the current becomes either stable due to the dc term or very low. Immediately following the polarisation, the **de-polarisation** (or discharging, desorption) **current** i_{depol} can be measured by a subsequent short-circuiting of the sample, see figure 2. According to the superposition principle and neglecting the second term in equn.(9) which is again a very short current pulse, we get for $t \geq (t_0 + T_C)$

$$i_{depol}(t) = -C_0 U_C [f(t) - f(t + T_C)]. \quad (10)$$

T_C is the time during which the step voltage for polarisation was applied. **This current is of opposite polarity.** The second term in this equation can be neglected, if T_C was already of long duration or the depolarisation current vanishes. Then the depolarisation current becomes directly proportional to the dielectric response function $f(t)$.

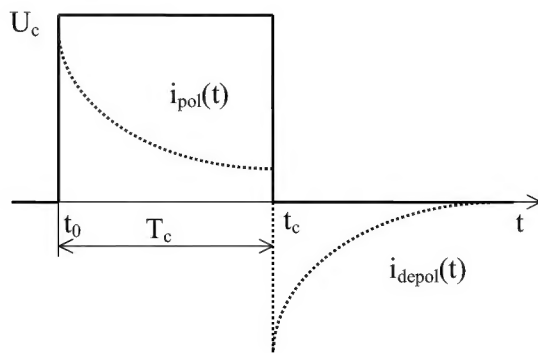


Figure 2: Principle of relaxation current measurements.

In practice, the polarisation and depolarisation or "relaxation" currents are measured with a "two

electrode" technique as sketched in figure 3. The measured currents are then defined by the selected electrode arrangement and can be sensed at virtual earth potential. The complex insulation system of a power transformer is a typical example for such an application.

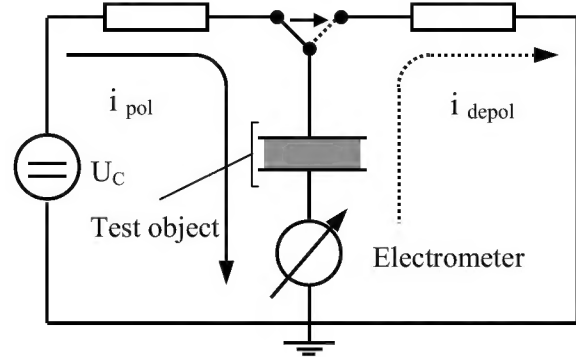


Figure 3: Principle of test arrangement for the "PDC" measuring technique.

Finally, an example of recently performed relaxation current measurements is shown in figure 4. It is taken from investigations concerning the dielectric response of oil-impregnated pressboard with the moisture content (m.c.) as a parameter. Preparation and test conditions of the samples can be found within the original publication [5]. Here, all measurements started 1 s after voltage application (i_{pol}) and after short circuit (i_{depol}). From the selected results it can be recognised, that only for the higher moisture content the final value of the polarisation current could be reached, though the measurements lasted up to 200'000 s, i.e. about 56 hours. Representation of such results in log-log-scale is paramount due to the large dynamic of the quantities.

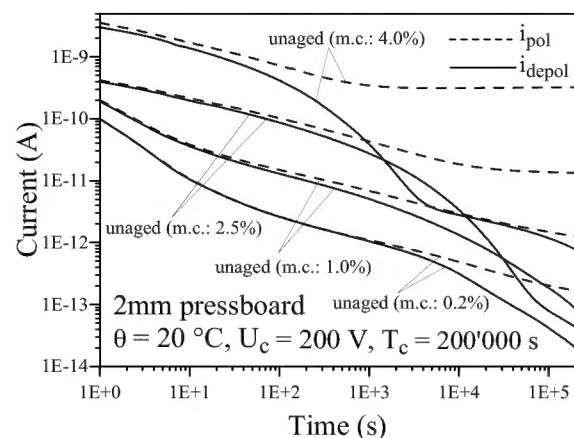


Figure 4: Relaxation currents of unaged samples with different moisture contents.

4 Dielectric response in frequency domain

An analytical transition from time to frequency domain can be executed by means of Laplace- or

Fourier transformation. This is shown by means of equations (6) and (8) in the following revised form, in which an ideal step response for the total current density of an ideal dielectric response function $f(t)$ considering also *instantaneous* polarisation processes are assumed:

$$\begin{aligned} j(t) = & \sigma_0 E(t) + \varepsilon_0 \frac{dE(t)}{dt} + \\ & + \varepsilon_0 \frac{d}{dt} \int_0^t f(t - \tau) E(\tau) d\tau \end{aligned} \quad (11)$$

With

$$j(t) \Rightarrow j(p); E(t) \Rightarrow E(p); f(t) \Rightarrow p E(p); f(t) \Rightarrow F(p);$$

and considering the convolution of the last term in this equation we get with p being the Laplace Operator:

$$j(p) = \sigma_0 E(p) + \varepsilon_0 p E(p) + \varepsilon_0 p F(p) E(p). \quad (12)$$

As p is nothing else than the **complex frequency** $i\omega$, we can reduce the equation to

$$\underline{j}(\omega) = \underline{E}(\omega) [\sigma_0 + i\omega\varepsilon_0(1 + \underline{F}(\omega))]. \quad (13)$$

Thus it becomes obvious, that $\underline{F}(\omega)$ is the Fourier Transform of the dielectric response function $f(t)$ or the complex susceptibility $\underline{\chi}(\omega)$:

$$\begin{aligned} \underline{\chi}(\omega) = \underline{F}(\omega) = \chi'(\omega) - i\chi''(\omega) \\ = \int_0^\infty f(t) \exp(-i\omega t) dt \end{aligned} \quad (14)$$

Note that the frequency scale is now $0 \leq \omega \leq \infty$! Combining equations (13) and (14) shows the well known relationship

$$\begin{aligned} \underline{j}(\omega) = \{ \sigma_0 + \varepsilon_0 \omega \chi''(\omega) + \\ + i\omega\varepsilon_0[1 + \chi'(\omega)] \} \underline{E}(\omega). \end{aligned} \quad (15)$$

The complex electric displacement $\underline{D}(\omega)$ can now be expressed by the *relative*, but *complex dielectric permittivity*, $\underline{\varepsilon}(\omega)$, with the relation:

$$\begin{aligned} \underline{D}(\omega) = \varepsilon_0 \underline{\varepsilon}(\omega) \underline{E}(\omega) \\ = \varepsilon_0 [1 + \chi'(\omega) - i\chi''(\omega)] \underline{E}(\omega) \end{aligned} \quad (16)$$

where:

$$\begin{aligned} \underline{\varepsilon}(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega) \\ = (1 + \chi'(\omega)) - i\chi''(\omega). \end{aligned} \quad (17)$$

Actual measurements of this dielectric response in frequency domain are difficult to perform, if the frequency range becomes large. Usually a " $C - \tan\delta$ " measurement is applied for a single power frequency. New instruments can cover, however, some decades in frequency range. Note, that according to equn. (15) such instruments **can not distinguish between** the current contribution of the

"pure" dc conductivity σ_0 and that of the (inherent) dielectric loss $\varepsilon''(\omega)$. This means that the effective *measured* relative dielectric permittivity $\tilde{\varepsilon}_r(\omega)$ is different from the relative permittivity $\varepsilon_r(\omega)$ as defined in equations (16) and (17). Then the effective relative dielectric permittivity $\tilde{\varepsilon}_r(\omega)$ is defined from the following relation:

$$\underline{j}(\omega) = i\omega\varepsilon_0 \tilde{\varepsilon}_r(\omega) \underline{E}(\omega). \quad (18)$$

Therefore:

$$\begin{aligned} \tilde{\varepsilon}_r(\omega) = \varepsilon'_r(\omega) - i[\varepsilon''_r(\omega) + \sigma_0/\varepsilon_0\omega] \\ = 1 + \chi'(\omega) - i[\chi''(\omega) + \sigma_0/\varepsilon_0\omega], \end{aligned} \quad (19)$$

and the "dielectric dissipation factor", $\tan\delta$,

$$\tan\delta(\omega) = \frac{\varepsilon''_r(\omega) + \sigma_0/\varepsilon_0\omega}{\varepsilon'_r(\omega)}. \quad (20)$$

The real part of equn. (19) represents the capacitance of a test object, whereas the imaginary part represents the losses. **Both quantities will depend on frequency.** Often, this fact is not appreciated, if only one single frequency is applied for the measurement. As ageing effects will change these magnitudes in quite different and specific frequency ranges, new diagnostic tools have to take care for this effect.

Measurements in the frequency domain need voltage sources of variable frequencies; these measurements become **very lengthy** if very low frequencies are considered. At least 2 to 3 cycles of an ac voltage are in general necessary to quantify the amplitudes and phase shift between voltage and currents. Therefore, up to 3'000 seconds can be necessary to get a single value only of C and $\tan\delta$ for a frequency of 1 mHz!

Figures 5 and 6 display the frequency range for the

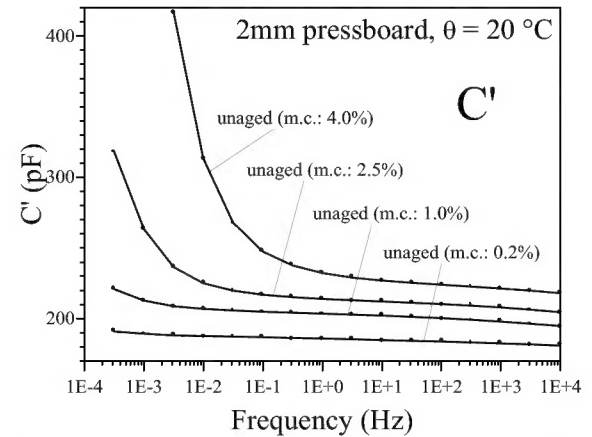


Figure 5: Real part of the complex capacitance of the pressboard samples, figure 4.

(real part of the) capacitance $C' = \varepsilon' C_0$ and dissipation factor of the pressboard samples as used in figure 4. The measurements have been made with

a special "dielectric spectrometer" [5, 6] for selected individual frequencies, which can be identified by the straight lines between measuring points. The results show, that the m.c. of the pressboard affects the low and very low frequencies much more than the power frequency, this for the dissipation factor as well as for the capacitance, C' ; this increase is obviously caused by the conductivity of water and thus increased interfacial polarisation inside the board.

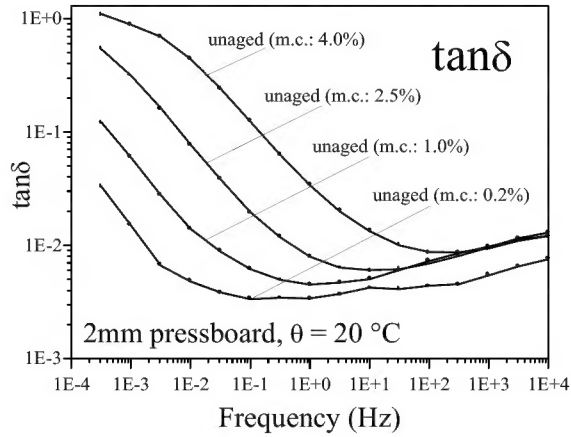


Figure 6: Dissipation factor $\tan\delta$ of the pressboard samples, Fig. 4.

5 Measurement techniques related to Dielectric Response

Ageing of insulation materials can be detected by its dielectric response in any of the two domains. But also many other methods exist as based on other physical reactions, as e.g. changes in chemical, mechanical or optical behaviour. Since many years such methods are applied to power transformer diagnostics, as e.g. by DP determination, oil parameter analysis including DGA or HPLC, or Carl Fischer tests for detecting moisture in oil and paper, for which a very large amount of publications does exist. This paper, however, is completely restricted to dielectric response techniques, which can be applied to any kind of equipment. The test objects are treated as "black boxes" accessible only by their terminals. The disadvantage of dielectric response measurements in either of the two domains is their "off-line" character, i.e. the equipment must be switched off from the power transmission voltage.

5.1 Principles in Time Domain

A **single Return or Recovery Voltage** measurement is the oldest method to qualify dielectric properties (permittivity and losses) of "anomalous" dielectrics, defined by not only a single relaxation time, see e.g. [7, 8]. Only the principle is recalled in figure 7: To get complete information, similar to fig. 1 a step voltage U_0 is applied across the electrodes of the completely discharged object. After a short grounding (short-circuiting) period, a recovery voltage, $U_R(t)$, can then be measured under open-

circuit conditions, if the input impedance of the voltmeter is very high. The source of the recovery voltage are the relaxation processes inside the dielectric material, i.e. the depolarisation current, $i_{\text{depol}}(t)$, which a voltage builds up on the electrodes of the test object. The grounding period shall be much less than 1 second so that only the "instantaneous" polarisation processes disappear.

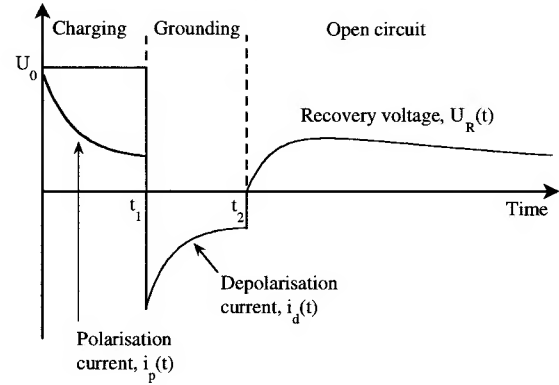


Figure 7: Principle of a Return Voltage measurement. Charging with U_0 during $0 \leq t \leq t_1$, grounding period from $t_1 < t \leq t_2$, for $t > t_2$, the recovery voltage is measured at open circuit conditions.

$U_R(t)$ can be calculated numerically if the dielectric response $f(t)$ of the test object (chapter 3) has been measured and if the duration of the grounding period, $(t_2 - t_1)$, together with other boundary conditions are taken into account [14]. The phenomena, however, can easiest be explained if we represent the dielectric by an *equivalent circuit* which is able to explain all measurements in time domain: As already shown in chapter 3, for "slow" polarisation processes the function $f(t)$ and thus the relaxation currents are monotonically decreasing, see fig. 4. These currents can be simulated by a sum of exponential functions as shown in [9] and elsewhere. This sum is, together with the power (high) frequency capacitance $C_\infty = \epsilon_\infty C_0$ as determined by conventional methods and the final value of the insulation resistance R_0 (equivalent to σ_0), the origin of this well known and general equivalent circuit, see figure 8. If this circuit is charged with a voltage source U_0 during $0 \leq t \leq t_1$,

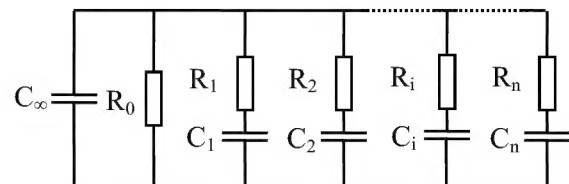


Figure 8: Equivalent circuit to model any linear dielectric.

the individual polarisation currents including the constant current through R_0 will flow into the circuit, charging instantaneously C_∞ and, with some delay,

the RC-elements according to their time constants. Depending on how long (t_1 !) the object is charged, the different polarisation processes as represented by the RC elements become either fully or only partly activated. A short grounding period from $t_1 < t \leq t_2$ will only discharge C_∞ but if this period is larger, also the slower polarisation processes start to relax. As soon as this short circuit is opened for $t > t_2$, the recovery voltage is measured at open circuit conditions, as the polarisation processes (or RC elements), which were either not or only partly relaxed during the short circuit period, will partly discharge into C_∞ and R_0 . The magnitude of the return voltage is thus always proportional to U_0 .

This method can be traced back to the beginning of the last century and was originally applied due to the difficulties in measuring small (depolarisation) currents. It was, however, always possible to measure voltages with electrostatic voltmeters, the input impedance of which is extremely large. The application of this method is of advantage if the "ground" terminal of the test object is not accessible. In Germany, at least one measuring system based on this method is commercially available [15].

If this ancient method is nowadays again applied, it was triggered by the appearance of a similar, but specialised method called simply "**RVM-technique**". The method, originally proposed in [10] and somewhat later commercialized [16], became attractive for diagnosing transformer insulation as it was claimed that the moisture content in the pressboard of the complete insulation system can be quantified by analysing a so-called "polarisation spectrum" resulting from the measurement. This "spectrum" is performed by applying a series of charging voltages U_0 to the test object, followed by the short circuiting as explained before, at each step increasing the charging time $t_1 = t_c$ and the short circuiting time $(t_2 - t_1) = t_g$ and using a fixed ratio of $(t_c/t_g) = 2$. During these periods, nothing is measured. After t_g has elapsed, the recovery voltage is recorded and from its peak value, the amplitude U_{Rmax} is quantified and plotted as a function of t_c . This dependency is called "polarisation spectrum" as its maximum appears indeed at a t_c -value, which agrees with a **single** time constant RC of our equivalent circuit, fig. 8. The method, however, is very lengthy as after each measuring cycle (the longest of which is 10'000 s) the insulation system must be discharged to prepare the next cycle. The method is thus fully based on *depolarisation* currents only which are, depending on the charging period, incomplete as only a part of these currents is used to build up the individual return voltages. - Instead of performing such a lengthy measurement, it is possible to *compute* the "polarisation spectrum" and its parameters if the dielectric response function $f(t)$ is known.

A quite new instrument, the **PDC Analyser**, as described recently in [11] and manufactured by a

Swiss company [17], measures a complete set of polarisation and depolarisation currents and thus also the response function $f(t)$, examples of which have already been shown in fig. 4. The default software of this instrument calculates all other quantities as e.g. insulation resistance in function of time, all kinds of "Polarisation Indexes", single Return Voltages or "polarisation spectra" as applied by the RVM-technique, and complex capacitance including loss factor in the frequency domain. Some examples of application and evaluation are shown in chapter 6.

5.2 Principles in Frequency Domain

The measurement of "C-tan δ " at power frequency (i.e. at one single value in the frequency domain) by means of bridge circuits, which are based on "standard capacitors", is well known. Since some years this quantity is sometimes measured at 0.1 Hz in combination with a low frequency HV test equipment as used for diagnostic tests of medium-voltage PE cables, the loss factors of which are sensitive to chemical treeing. A quite large frequency range is now covered by a new instrument called "**IDA 200**" manufactured by a Swedish company [18]. This "Insulation Diagnostic Tool" measures C-tan δ from 0.0001 Hz - 1000 Hz and covers thus also the low and very low frequency range which is most prone to ageing effects.

6 Example: Power transformer insulation

Finally, an example for the application of one of the new diagnostic tools is presented based on *time domain* (PDC) measurements. The example is taken from very recent investigations in the CIGRE Task Force 15.01.09.

In the course of the investigations, a test object modelling power transformer insulation systems was designed, constructed and used. The measurements as performed on this model are based on the 3 methods as explained in chapter 5 (RVM-technique, PDC Analyser and IDA 200). The design of the test object and the goal of the investigations was already published in [12]. A much more extensive publication from the aforementioned Task Force will be available in 2002.

The model can be characterised as follows:

___ Metal tank (ca. 490x1040x1560 mm) with bushings to connect the inside flat electrodes between which different insulation configurations have been sandwiched.

___ Each insulation configuration consisted from flat plates of pressboard ("Kraft Thermo 70") with or without oil gaps between the electrodes. Pressboard plates have been fixed in the middle of the whole gap between electrodes by means of pressboard spacers.

In the following figures, the curves are marked by *codes* indicating the insulation configurations. The

code is used to quantify the dimensions of the whole gap by the thickness (in mm) of board and oil as follows:

01: 10/0; **02:** 2/10; **03:** 4/10; **04:** 10/10.

The effective area of the electrodes is about 1 m². The "instantaneous" capacitance as measured with 50 Hz ranges from about 4.8nF to 2.35nF.

Figure 9 shows all 4 sets of relaxation currents as measured on the either "pure board"- configuration 01 or the multi-layer configurations of code 02 to 04. The currents have been recorded just 1 s after voltage application or short-circuiting, and measurement periods have been 5'000 s each. The shapes of the currents for these 4 configurations can be subdivided into 2 groups: The multi-layer configurations 02 to 04 are characterised by their *pronounced exponential shape* at short times of less than about 200 s. This kind of shape is typical for PDC measurements on all kinds of HV power transformers. They are essentially produced by the formation of the *interfacial polarisation* between oil gaps and pressboard barriers. It can well be identified from these shapes in log-log-scales that their dominating time constants increase with the thickness ratios of oil gaps to pressboard barriers. The dielectric response of the pressboard becomes more apparent at long times, at which the depolarisation currents are quite well in parallel indicating the identity of the dielectric response function of the pressboard material as used to reach different thickness (from 2 to 10 mm) of the barriers.

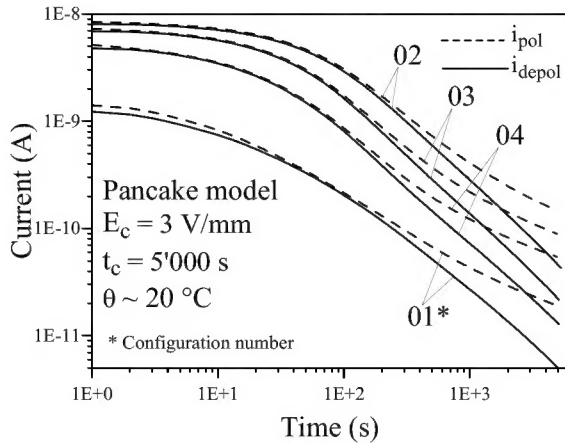


Figure 9: Relaxation currents measured on 4 different configurations of the "pancake" model. The measurement have been performed for a voltage to electrode spacing ratio of 3 V/mm.

The (nearly) homogeneous gap of configuration 01 behaves quite different, as the *initial* shape of the currents is not pronounced exponential. A comparison with e.g. the relaxation current shapes in figure 4 (unaged, 1% m.c.) shows that still some small oil gaps exist in series to the pressboard, confirmed by not ideal electrode systems not further discussed here.

Figure 10 presents the *calculated* "polarisation spectra" for all 4 configurations 01 to 04 of the model and for a charging voltage of 1 V. (In a later fig. 14 it will be shown that such calculations are in good agreement with spectra as measured by the RVM method.) The results show that the position of the peak value in "polarisation spectrum" does change in dependence of geometry. For the configs. 02 to 04, this maximum is due to the "macroscopic" interfacial polarisation and its geometric position at the interface between oil gaps and pressboard. This fact can also be calculated by assuming a simple Maxwell-Wagner interfacial polarisation process. In this model, 2 series-connected dielectrics with losses are assumed. Each dielectric can then be modelled by - for our example - the conductivity and relative permittivity of the oil (σ_{oil} , ϵ_{roil}) and of the pressboard (σ_{Board} , ϵ_{rBoard}). Then the time constant τ of the interfacial polarisation is given quantitatively by the following equation, where d_{oil} and d_{Board} are the thickness of oil gap and pressboard barrier [13].

$$\tau = \epsilon_0 \cdot \frac{d_{Board} \epsilon_{rOil} + d_{Oil} \epsilon_{rBoard}}{d_{Board} \sigma_{Oil} + d_{Oil} \sigma_{Board}} \quad (21)$$

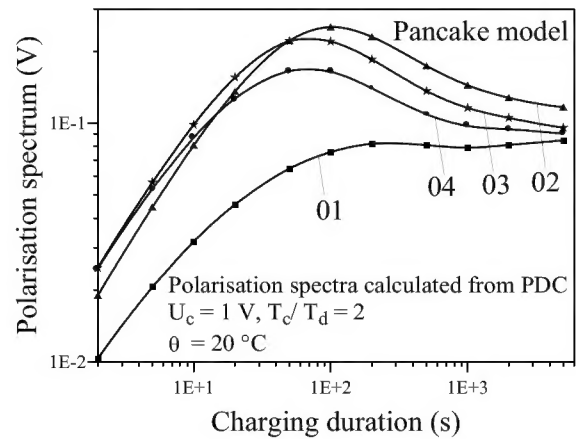


Figure 10: Calculated polarisation spectra of all configurations. Calculated curves are based on the default software of the PDC Analyser.

Though in equn. (21) the much more complex dielectric properties of the pressboard are not taken into account and only simulated by a single time constant, a numerical evaluation with approximate values for both components would already show quite good agreement with the results as measured. This equation can *not* simulate the spacers as applied to fasten the board within the gaps, but it shows already for the different ratios of oil gaps to board thickness the change of the "dominant" time constants, which decrease in magnitude if this relationship decreases.

The default software of the "PDC Analyser" calculates for all measured currents (see fig.9) the specific equivalent circuits (see fig. 8) so that the transition to frequency domain is easy to perform. In

figure 11 the results of such calculations are displayed for the most interesting configurations 02 to 04 and compared with the measured values of capacitance $C'(\omega)$ and dissipation factor $\tan\delta(\omega)$ as registered by the dielectric spectrometer "IDA 200"[14].

The comparison shows the good agreement of measured and calculated values down to very low frequencies. The maxima in the $\tan\delta$ curves and the significant increase of capacitance at low frequencies confirm again the predominant influence of interfacial polarisation on the total dielectric response of multi-layer arrangements.

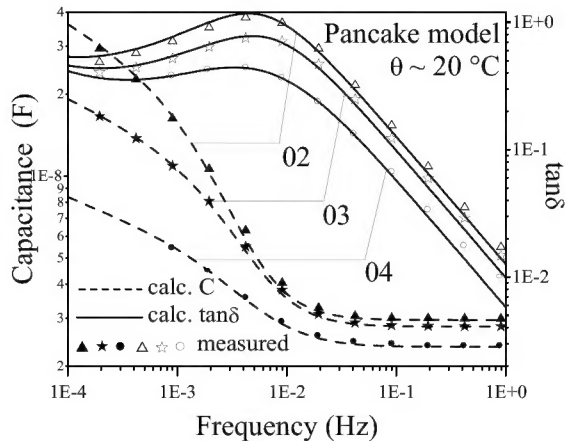


Figure 11: Comparison between calculated and measured capacitance and dissipation factor $\tan\delta$ values for configurations 02 to 04.

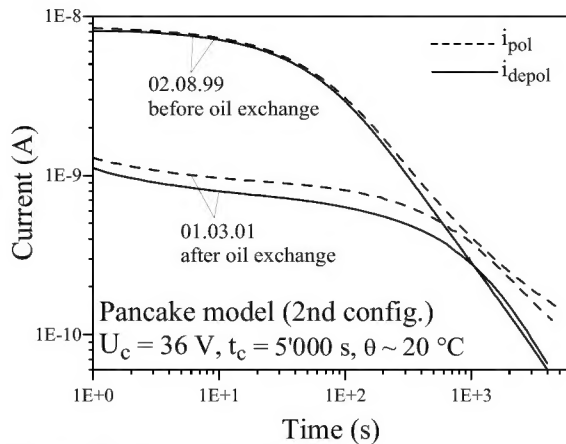


Figure 12: Measured relaxation currents on configuration 02 before and after oil exchange.

All measurements as shown in figures 9 and 11 have been made with the original new oil of type "Nynas Nytro 10GBN" with a conductivity of about 2 pS/m (20°C). As also the influence of the oil and its conductivity should have been investigated, it was decided to replace it by an oil of different origin with a significantly lower conductivity. The new type was "Shell Diala D" with $\sigma = 0.24$ pS/m (21°C). For configuration "02" figure 12 shows now the measured relaxation currents before and after oil

exchange. Now, the initial amplitudes dropped by a factor of about 9 and the duration of the nearly exponential decay of the currents is heavily prolonged. This decrease of the initial current amplitude and the shift of the time constant of interfacial polarisation to long times is thus only due to the decrease of oil conductivity.

The significant changes must also appear in the frequency domain. Figure 13 shows the calculated and partly measured dependencies of capacitance $C'(\omega)$ and dissipation factors $\tan\delta(\omega)$. The calculated values are determined from the relaxation currents as displayed in fig. 12. In the low frequency domain, the increase of the capacitance takes now place for much lower frequencies for the low conductivity oil as the process of interfacial polarisation between oil and pressboard needs much more time. This increase in capacitance is due to the simple fact that the electric field in the oil gap will more or less vanish with time; therefore, for extremely low frequencies, the capacitance of the pressboard alone will appear.

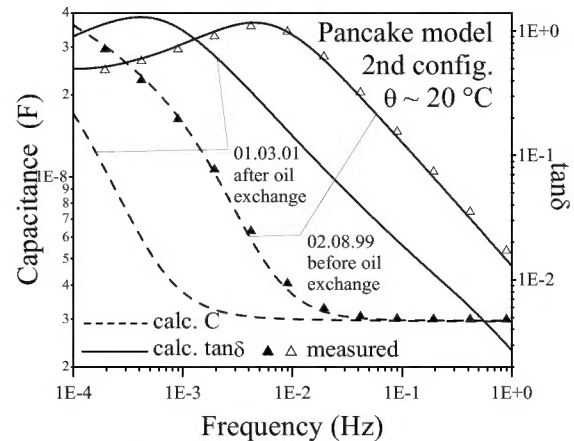


Figure 13: Comparison of calculated capacitance and $\tan\delta$ curves before and after oil change. .

Finally, figure 14 displays the two polarisation spectra as calculated by the PDC Analyser from the measured relaxation currents (fig. 11). For this calculation the charging voltage was set to 500 V permitting the direct comparison with measured values as performed by the RVM technique, marked by triangles and stars.

This figure shows again the significant influence of oil conductivity on the time position of the first maximum in the polarisation spectrum and the good agreement between calculated and measured values, although the RVM meter quantifies a somewhat different insulation system than the PDC Analyser (1-terminal against 2-terminal measurement).

These investigations confirm that the main (or first) maximum in the "polarisation spectrum" of the RVM technique for multi-layer arrangements is due to the interfacial polarisation and that its time position is dependent on the geometrical layout (thickness ratio of oil gap to pressboard barrier) and

conductivity of oil. Therefore, the time position of the first maximum cannot be correlated with the moisture content of the pressboard material.

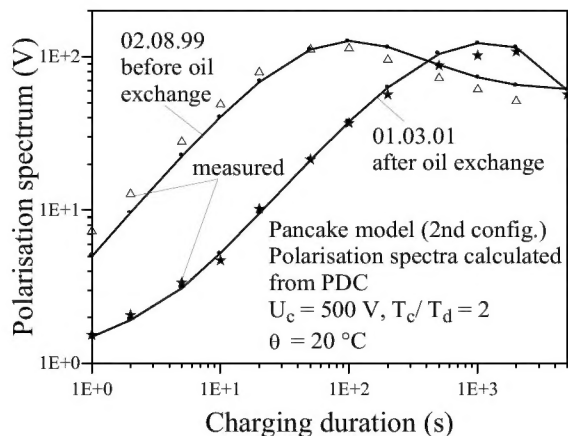


Figure 14: Comparison of calculated and measured polarisation spectra of configuration 02 before and after oil change.

The results as presented confirm already the possibility to distinguish between oil and impregnated pressboard as applied for insulation systems in power transformers. Much more quantitative data can be evaluated if the geometry of the insulation system including spacers etc. is quantitatively taken into account. This can be done by a specific software for the PDC Analyser which is based on dielectric response functions $f(t)$ of otherwise investigated materials and its comparison with measured data. As an example, the actual oil conductivity of the test object can immediately be determined as the first part of the polarisation current is completely governed by this conductivity. Similar evaluations are possible if frequency domain measurements have been made.

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